Paper ID #37442

Design, Fabrication, and Testing of Next Generation Desktop Learning Modules for Chemical and Mechanical Engineering Education

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Abstract

In this paper we report on the development and testing of hands-on desktop learning modules for transport courses in the Chemical and Mechanical Engineering disciplines. Two modules were developed to demonstrate fluid mechanics-related concepts, while two other modules were created for energy transport in heat exchangers. These devices are small, inexpensive, and made of see-through polycarbonate plastics using injection molding. These desktop learning modules are particularly suitable for use in undergraduate classrooms in conjunction with lectures to illustrate the working mechanism of devices seen in an industrial setting. Experiments are performed to understand the flow behavior and heat transfer performance on these modules. Our results show an excellent agreement for hydraulic head loss, volumetric flow rates, and overall heat transfer coefficients between experimental data and the corresponding theory, justifying the design and use of these devices in the classroom. Furthermore, we have measured student learning gains through pre-and posttests for each module based on in-class implementations at different universities. Assessment of student learning outcomes shows significant improvement in conceptual understanding when these modules are used in the undergraduate class.

1. Introduction

Transport courses such as fluid mechanics and heat transfer are core subjects in mechanical and chemical engineering disciplines. Theoretical concepts covered in those courses are highly complex and students need to put substantial effort to understand these concepts. Because of that most of the classroom time is usually spent to teach those theories and associated postulates. However, our experience suggests that students do not always understand those transport-related concepts that are extensively encountered in various industrial devices. This arises because the traditional teaching method is not optimized for all kinds of learning styles. The traditional classroom teaching methods are especially unsuitable for tactile or kinesthetic learners who learn through doing or experiencing. In that case, the need of kinesthetic learners can be effectively addressed by introducing hands-on learning in the classro m [1].

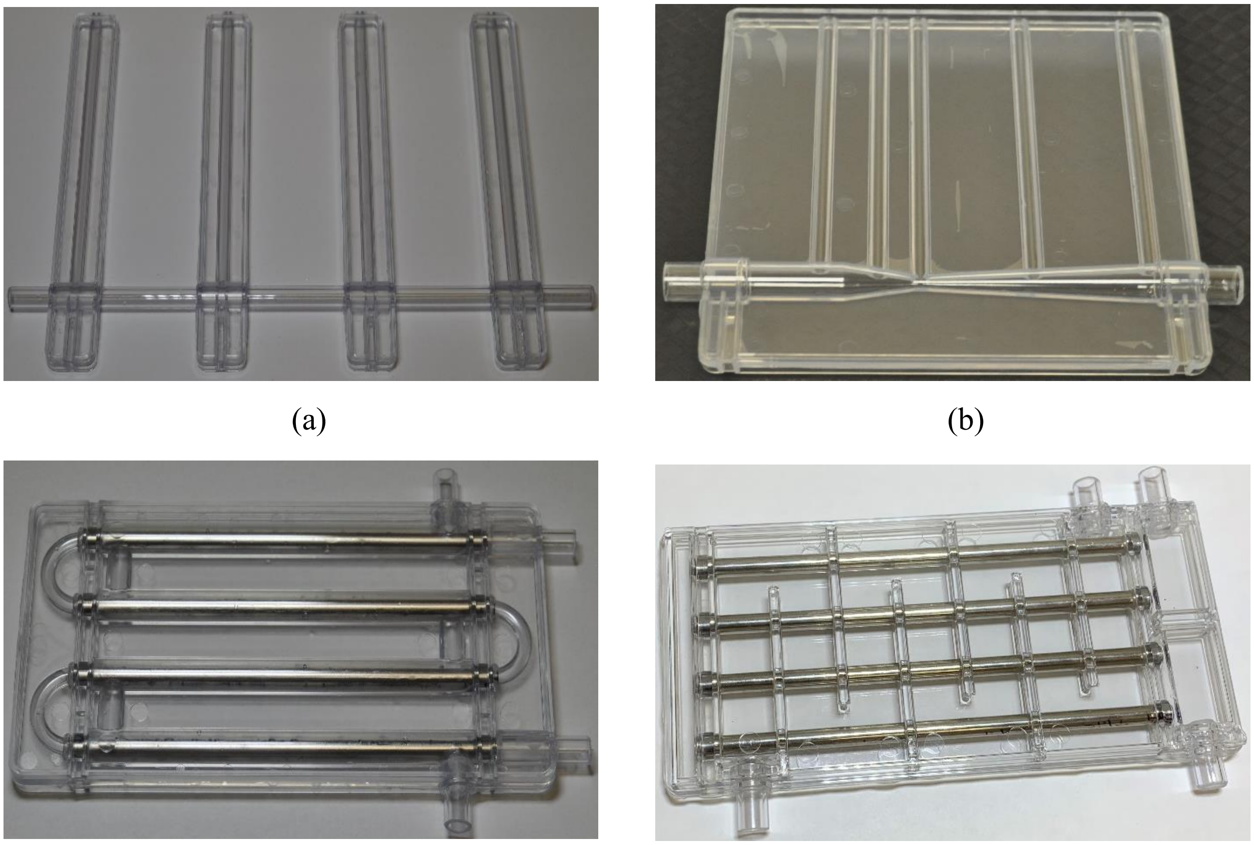
Hands-on or experiential learning is an approach in which students engage in the learning process with direct experience and rigorous thinking. Hands-on learning allows students to use their acquired skills during the learning process and creates opportunities for developing new skills [2]. To incorporate hands-on learning experiences in the undergraduate Mechanical and Chemical Engineering classroom, we have developed low-cost desktop learning modules (DLM) [3-7]. Two modules, namely a hydraulic (head) loss measurement device, and a venturi meter are developed to demonstrate fluid mechanics-related concepts, while two other modules, namely double-pipe and shell-and-tube heat exchangers, are created for energy transport in heat exchangers. By using a fluid mechanics concept inventory, Fraser et al. [8] found that sophomore chemical engineering students have the greatest difficulties with pressure measurements and fluid flow through pipes when the diameter is changing between two sections. We expect that implementation of the fluid mechanics modules will address concepts of continuity and pressure change for fluid flow through straight pipes and pipes with changing diameter. Similarly, implementation of the heat transfer modules will address concepts of energy conservation, heat transfer driving mechanism, and the combined effects of geometry and flow rate on the various heat transfer resistances in a heat exchanger. These devices are small, safe, and adequately rugged for repeated classroom use. In addition, the cost of these devices is like that of a textbook, making it affordable to deploy large numbers of units in a classroom for extended hands-on work. Carlson and Sullivan [2] identified that visibility is a key element to studying engineering because much of engineering is visually interesting. Therefore, these modules are made of see-through polycarbonate plastic which offers visualization of complex transport phenomena. Furthermore, for this study, we chose low-cost desktop learning modules that closely resemble miniature versions of industrial equipment that perform according to the various conservation principles, and standard correlations already exist for different transport characteristics.

We believe that once students have participated in DLM implementations, they will know the basic mass and energy conservation laws, be able to explain how different parameters affect the frictional head loss, pressure and velocity, and rate of heat transfer, and be able to compare the experimental measurements with the corresponding theoretical predictions. To assess these student learning outcomes, in this paper, we have used the pre/posttests approach because of its broad acceptance [9]. The pre- and posttest scores are finally used to assess the student's conceptual understanding of the subject matter before and after the desktop learning modules implementation. Moreover, in this paper, performance of hydraulic loss DLM is tested by comparing experimental data with corresponding theoretical predictions to justify the design and use of these devices in the classroom.

2. Methods

2.1 Design and Fabrication

Two fluid mechanics cartridges (hydraulic loss and venturi) and two heat exchanger cartridges (double-pipe and shell-and-tube) are designed in CAD software. The design philosophy is to create transparent, highly visual devices that are inexpensive, portable, and simple to operate with minimal instrumentation. Injection molding is chosen as the manufacturing method, which is best suited to mass production of inexpensive, robust parts that could hold dimensional tolerances for reproducible fluid flow and heat transfer performance. To simplify assembly for low-cost and rapid production, all designs involve book-matched halves that are assembled with additional tubing pieces using a UV-curable adhesive to produce devices with various internal flow paths. Polycarbonate is chosen as the plastic for the injection-molded parts to give both good transparency and high impact strength. The flattened shell-and-tube heat exchanger design is a compromise that allows for ease of assembly and visibility of operation while still allowing performance evaluation using standard heat-transfer coefficient correlations.



(a) (b)

(c) (d)

Fig. 1. Images of desktop learning modules: (a) hydraulic loss cartridge, (b) venturi meter cartridge, (c) double pipe heat exchanger cartridge, and (d) shell and tube heat exchanger module.

The CAD designs are sent to an injection-molding company to produce the molds and injection-molded parts. To assemble the DLMs, one half of the injection-molded tubing piece is held in a jig on a robotic adhesive applicator and a pre-programmed pattern of adhesive is applied. Next, the other tubing piece is placed by hand, followed by robotic application of adhesive over the top of that tubing piece with another pre-programmed pattern, to complete seals around the tubes. Polycarbonate tubes are used for inlets and outlets on the venturi, double-pipe heat exchanger, and shell-and-tube heat exchanger. A 12-inch long, 1/4-inch ID (3/8-inch OD) polycarbonate tube with holes aligned with the molded manometer tubes is used for the hydraulic-loss DLM. Four stainless steel tubes (6-inch by 1/4-inch OD, 20-BWG) are used in each heat exchanger. After the tubing is placed and the tube-sealing adhesive pattern applied, the matched injection molded part is placed and clamped in the jig with a top plate that has a pattern of holes to allow UV light to enter for curing the adhesive. The clamped assembly is placed in a UV chamber and cured for 1 minute. The assembly is then removed from the clamping jig and adhesive curing is completed in the UV chamber. Completed DLMs are checked for leaks before shipping to users.

All 4 DLMs are designed with grooves for the attachment of stands that support the DLM at near eye level when the setup is on a tabletop. Miniaturized pump(s) are used to generate flow through these DLMs. We chose small off-the-shelf submersible water pumps (12V, 4W) that can run on a single rechargeable 9V battery. To reduce the cost, pump assemblies are designed to work with any one of these DLMs. The pump wires are soldered to a battery holder with an integrated switch and the connections are sealed with heat-shrink tubing. The pumps are attached to a 1/4-turn ball valve by a short piece of silicone tubing allowing for control of flow rate. Several other off-the-shelf components are needed including tubing, tube fittings, and digital thermometers.

2.2 *DLM Performance*

The performance of the completed cartridges has been characterized by careful experimentation and compared with predicted performance using existing theories and correlations. For example, the heat transfer performance of the double-pipe heat exchanger is found to agree very well with predictions from industrial correlations [5]. In this paper, we report on performance testing of the hydraulic loss DLM. The hydraulic loss experimental setup, shown in Fig. 2, is used to collect all data to compare its performance with the theoretical prediction of major (frictional) head loss. For this hydraulic loss unit, besides the DLM cartridge, the complete setup requires several auxiliary elements which include one 3/8-inch OD U-bend for the inlet, one 3/8-inch OD 90° elbow for the outlet, one tubing adapter to connect the pump to the inlet U-bend, one universal stand (2 legs), one pump assembly, one rechargeable NiMH 9V (280 mAh) battery, and two 1-liter beakers.

The experiments are carried out by graduate students in a laboratory environment. The range of flow rates is limited, on the low end, by air entrainment into the pipe from the downstream manometer tube near the pipe exit, and, on the high end, by overflow of water from the manometer tube near the pipe entrance. The allowable flow rate range was found to be from 13 to 27 mL/s. Flow rates are controlled by adjusting the quarter-turn ball valve attached to the supply pump. The measured volume flow rate, $\dot{V}_m$ is obtained by collecting water from the exit in a beaker and then dividing it by the time of flow. During that time, we also recorded the water column height in the manometers. Therefore, the experimental head loss can be given as

$$h_{L,Exp} = h_{in} - h_{out} \tag{1}$$

where h_{in} and h_{out} are the height of water columns in the inlet and outlet manometers, respectively. The flow velocity, v, is obtained by dividing the measured volume flow rate with the cross-sectional area of the pipe. The theoretical head loss was calculated based on the Darcy-Weisbach equation

$$h_{L,Th} = \frac{fLv^2}{2gd} \tag{2}$$

where d is the pipe inner diameter, L is the length of the pipe section between the inlet and outlet manometer tubes, g is the gravitational acceleration, and f is the friction factor. The friction factor is calculated based on the flow condition, which is identified by calculating the Reynolds number, $Re = \frac{\rho v d}{\mu}$, where μ is the fluid viscosity and ρ is the fluid density. Since Reynolds number was greater than 2300 for all experiments, we used the Swamee-Jain equation [10] for the friction factor

$$f = \frac{0.25}{\left[log\left(\frac{\varepsilon/d}{3.7} + \frac{5.74}{Re^{0.9}}\right)\right]^2} \tag{3}$$

where ε/d is the relative roughness. For our analysis, we neglect the effect of roughness as DLMs are made of very smooth pipes.

2.3 Classroom Implementation

The LC-DLMs were implemented in the Mechanical Engineering class at the University of Central Oklahoma (UCO). The UCO is a metropolitan and primarily undergraduate institution. 30% of the UCO student population are non-traditional students, and about 30% of students are from ethnic minority or underrepresented populations. Non-traditional students are those who have study breaks between high school graduation and college study. The Mechanical Engineering program is housed in the engineering and physics (DOEP) department under the college of mathematics and science (CMS). Typical class sizes of the mechanical engineering courses are 20 – 25 students per semester. The low-cost desktop learning modules (LC-DLMs) are employed in the Fluid Mechanics (ENGR 3343) and Heat Transfer (ENGR 4123) classes. These are required classes for mechanical engineering majors. Usually, academically junior standing students take the fluid mechanics class, and senior standing students enroll in the heat transfer class. Both classes have an additional 1-credit laboratory component which are generally taught by different instructors without coordination of the lecture class materials (or instructor). The instructor and the respective TAs conducted the mock experiments on each DLMs before actual implementation in the lecture class for smoother execution. Students who participated in this study provided their consent through a digital form. Although our IRB office determined that the study is exempt, we still requested consent so that the data could be shared in a public forum.

The venturi meter and hydraulic loss DLMs were implemented in the fluid mechanics class in fall 2021. The class size was 19. The hydraulic loss DLM was implemented in-person in the classroom, while the venturi meter DLM was done with an asynchronous virtual implementation. Pre-tests were conducted in the in-person classroom through a Qualtrics survey before the exposure of the topic and DLM implementation. However, it is important to note that students were exposed to similar topics in their laboratory class with a different lab instructor. In the classroom implementation, students worked in groups of four to assemble DLMs, conduct experiments, and collect data. The instructor went over the handout with students and discussed the answers related to the non-homework worksheet questions. For the virtual implementation of venturi meter DLMs, the instructor shared the WSU EDUC-ATE video link and clarified students' queries. In the recorded video, an instructor from WSU went over the worksheet and explained fundamentals of the pressure trends and velocities at the different cross-sections of the venturi meter for Bernoulli equation. For virtual implementations, the instructor also conducted the experiment and collected necessary data as instructed in the worksheet and shared those data in the video. Students used those data to do the calculations as instructed in the worksheet as part of their homework. Students were given one week to write and submit the report for both DLMs. The posttests were conducted in person in the classroom through the WSU EDUC-ATE website.

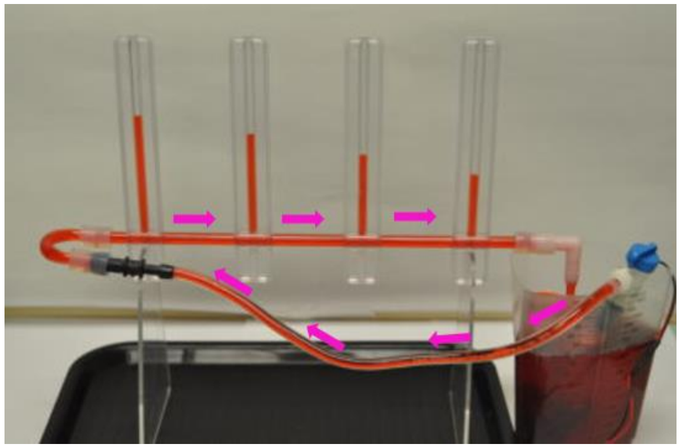


Fig. 2. Experimental setup for hydraulic loss measurement. Arrows indicate the direction of fluid flow.

The double-pipe and shell-and-tube heat exchanger DLMs were implemented in the heat transfer class during fall 2021, and the class size was 16. The shell-and-tube heat exchanger was implemented in-person in the classroom while the double-pipe heat exchanger was implemented asynchronously through the WSU EDUC-ATE website. In this asynchronous mode, students watched the recorded video of someone conducting the experiment for the double-pipe heat exchanger as provided in the WSU EDUC-ATE website. Similar to the venturi meter DLMs, the instructor on the recorded video demonstration explained and shared the collected data and students performed calculation as a part of their homework and submitted results as a report. Pre-tests were conducted before the introduction of the topic a week ahead. Although the additional 1-credit heat transfer laboratory class at UCO does not have an experimental setup on heat exchangers, students were exposed to the heat exchange topics in the thermal system design class in previous semesters with a different instructor. For in person shell-and-tube heat exchanger DLM, students were divided into four teams with 4 students each to conduct the in-class implementation. Like the hydraulic loss DLM, the instructor went over the DLM handout and clarified students' questions while students were conducting experiments and collecting data. Students submitted the completed worksheet for each DLM a week after the implementation. Like fluid mechanics DLMs, the posttests for both heat transfer DLMs were conducted in person in the classroom.

2.4 Assessment of Learning Outcomes

A pretest was taken before DLM activities to evaluate the existing knowledge level of the subject matter, while a posttest was conducted after the DLM activities to assess the updated knowledge of the subject matter.

2.4.1 Hydraulic loss experiment

The learning objectives of the hydraulic loss implementations include the ability to use the continuity equation and mechanical energy balance to predict velocity and pressure profiles in a pipe, the ability to measure frictional head loss, understanding the effect of Reynolds number, pipe length, and pipe diameter on the frictional head loss, the ability to calculate head loss using first principles and compare with experimental head loss. Therefore, pre- and posttest assessment questions are designed in parallel with the student learning objectives. The conceptual foci of each pre- and posttest question used in the hydraulic loss experiment are given in Table 1.

Table 1. The conceptual focus of hydraulic loss pre- and posttest questions

Question No	Conceptual Focus
Q1	Explore the parameters which reduce the head losses in a piping section
Q2	Apply the continuity equation to predict fluid velocity in a constant diameter coiled pipe
Q3 (A/B)	Identify the pressure profile along the pipe (part A) with appropriate reasoning (part B)
Q4 (A/B)	Predict the velocity profile with distance (part A) along a straight constant diameter pipe with proper reasoning (part B)

2.4.2 Venturi meter

The expected learning outcomes for the venturi meter DLM include the understanding of changes in fluid velocity and pressure as the fluid passes through a venturi meter, grasping the nonlinear effect of diameter change on the pressure and velocity, realizing the energy transformation (one form to another) as fluid passes through the venturi meter, the ability to calculate flow rate from the measured pressure difference and compare with the measured flow rate, and the ability to estimate the venturi discharge coefficient for the venturi module used in the implementation. Therefore, pre- and posttest assessment questions are designed in parallel with the student learning objectives. The conceptual foci of each pre- and posttest question used in the venturi meter experiment are listed in Table 2.

Table 2. The conceptual focus of venturi meter pre- and posttest questions

Question No	Conceptual Focus
Q1	Understand the concept of continuity at steady state for an incompressible fluid
Q2	Select the most realistic graph for pressure versus distance in the venturi
Q3	Select the most realistic graph for velocity versus distance in the venturi
Q4	Describe the energy transformation in the fluid due to quick expansion
Q5	Deduce the pressure profile from a given velocity profile
Q6	Select the most realistic pressure profile in a suddenly expanded pipe

2.4.3 Double pipe heat exchanger

The student learning objectives for the double-pipe heat exchanger include the identification of flow patterns for hot and cold fluids for a countercurrent flow arrangement, calculation of the heat transfer rate, understanding the difference between flow area and heat transfer area, and analysis of the effect of flow rate and inlet/outlet temperatures on performance. The conceptual foci of each pre- and posttest question used in the double-pipe heat exchanger experiment are listed in Table 3.

2.4.4 Shell & tube heat exchanger

The shell-and-tube heat exchanger is designed with several objectives which include the identification of flow types occurring in the heat exchanger, understanding of the difference between flow area and heat transfer area, determination of experimental heat transfer rates and overall heat transfer coefficient, and calculation of the overall heat transfer coefficient and comparison with the experimental value. The conceptual foci of each pre- and posttest question used in the shell-and-tube heat exchanger experiment are listed in Table 4.

Table 3. The conceptual focus of double-pipe heat exchanger pre- and posttest questions

Question No	Conceptual Focus
Q1	Identify the system boundary for energy balance to calculate the heat transfer rate
Q2	Understand the flow areas and heat transfer area in a double pipe heat exchanger
Q3 (A/B)	Justify the effect of heat exchanger length on the heat transfer rate
Q4	Analyze the effect of annulus side fluid velocity on the heat transfer rate
Q5	Understand the driving potential in a double pipe heat exchanger
Q6	Analyze the effect of cold-water flow rate and temperature on hot water outlet temperature

Table 4. The conceptual focus of shell-and-tube heat exchanger pre- and posttest questions

Question No	Conceptual Focus
Q1	Understand the types of flow occurring in a shell & tube heat exchanger
Q2	Deduce the mathematical expression for the heat transfer area
Q3	Evaluate the effect of baffles on the heat transfer rate
Q4	Judge the effect of cold and hot fluid inlet temperatures on the heat transfer rate
Q5	Quantify the shell side fluid velocity from the volume flow rate
Q6 (A/B)	Understand the influence of cold-water flow rate on hot water outlet temperature

2.5 Student t-test and effect size

A t-test is used to determine whether the difference between pre-test and posttest means is significant or not. Since the same students participated in both pre- and posttests, we have carried out a paired two-sample t-test for an average score. The null hypothesis used in this test is that the observed difference between pre-test and posttest means is due to chance alone. Therefore, the alternate hypothesis is that the observed difference between pre-test and posttest means is due to the implementation of DLMs in the classroom. For a paired two-sample t-test, the t-value is calculated using

$$t = \frac{\sum_i D_i}{\sqrt{\frac{N\sum_i D_i^2 - \left(\sum_i D_i\right)^2}{N-1}}} \tag{4}$$

where D_i is the difference between the pre-test and posttest score of student i and N is the sample size. The corresponding p-value is calculated from the t-value. All the analyses have been carried out in Excel and we have used a 5% level of probability i.e., $\alpha = 0.05$ as a criterion for acceptance of the alternate hypothesis.

While the t-test specifies whether implementations of DLMs significantly change students' scores or not, the effect size provides a quantitative measure of the change due to the implementation of DLMs. Since we have used a paired t-test for means, Cohen's d is an appropriate effect size for this case. The Cohen's d effect size can be given as

$$\text{Effect size} = \frac{Mean_{posttest} - Mean_{pretest}}{SD_{pooled}} \tag{5}$$

where pooled standard deviation (SD_{pooled}) can be given as

$$SD_{pooled} = \sqrt{\frac{SD_{pretest}^2 + SD_{posttest}^2}{2}} \tag{6}$$

3. Results and Discussion

In this section, we first compare performance test results of the hydraulic-loss DLM with relevant theoretical predictions. Then, we present results for student learning gains based on pre- and posttest assessments for all four DLMs.

3.1 Hydraulic-loss DLM Performance

The comparison between experimental and theoretical head loss is shown in Fig. 3 for different flow rates. As shown in this figure, the experimental head loss is slightly higher than the prediction, especially at higher flow rates. Since we did not use sophisticated devices to measure flow rates or height of the water column in the manometers, the discrepancy may arise because of the unavoidable errors in the measurements. But, as seen from the figure, overall, the experimental head loss is in line with the theoretical prediction which justifies the use of DLMs in the classroom.

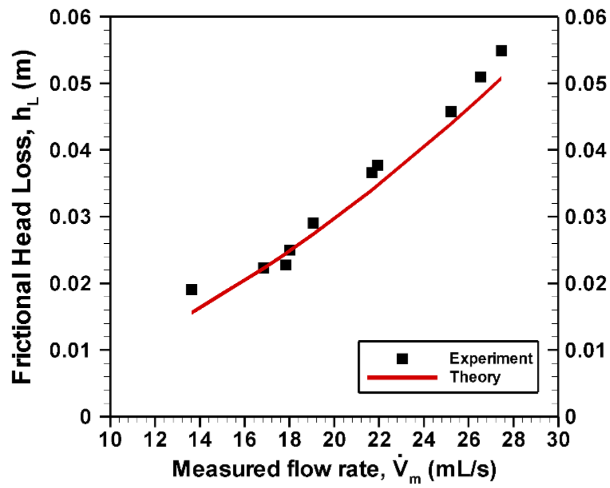


Fig. 3. Comparison of experimental major (frictional) loss vs theoretical major loss for hydraulic loss DLM cartridge.

3.2 Assessment of Student Learning Outcomes

Assessment results are summarized in Figs. 4-7. Pre-test and posttest scores are presented in terms of the average score with student t-test and Cohen's d effect size indicated.

3.2.1 Hydraulic loss experiment

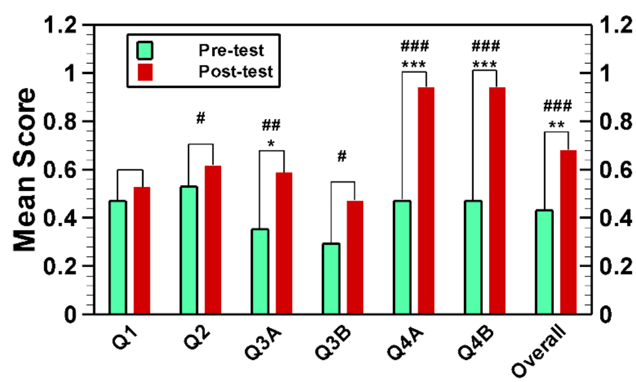


Fig. 4. Assessment results from hydraulic loss module implementation (N=17). #, ##, and ### indicates small, medium, and large Cohen's d effect size, respectively; while *, **, and *** indicates 0.05 ≤ p-value < 0.01, 0.01 ≤ p-value < 0.001 and p-value ≤ 0.001, respectively.

Fig. 4 shows the student performance on the pre-test and posttest for the hydraulic loss experiment before and after the DLM activity. As shown in the figure, for each question, the posttest mean score is higher than that of the pre-test mean score which indicates an improvement in student conceptual understanding. To answer Q1 correctly, students need to conceptualize the effect of each parameter on the pressure drop in a piping section based on the Darcy-Weisbach equation [11]. Although students calculated pressure drop based on the Darcy-Weisbach equation, they were not able to grasp the concept. As a result, there is no significant improvement from pre- to posttest. For Q2, students need to apply the continuity equation to predict the velocity through a coiled pipe. However, as seen by the statistics for this question, the result is not favorable as the average score is low and there is no significant improvement. We found that the unfavorable result arises because the fluid depicted in the question is flowing in the downward direction through the coil which may lead students to mistakenly believe that the flow accelerates. To answer Q3, students are required to understand the major loss and its linear dependency on the length of the pipe. Since the hydraulic loss experiment is designed to give a comprehensive understanding of major loss, we can expect a favorable result for this question. As seen by the statistics of Q3, there is significant improvement with a 95% confidence level in the selection of pressure profile (Q3A), however, there is no significant improvement in the reasoning (Q3B). This indicates that students just remember the fact that, in a constant diameter pipe, pressure decreases linearly and they select the correct pressure profile in the posttest. Again, Q4 requires understanding and applying the concept of fluid continuity to predict the correct answer. As shown by the statistics for this question, there is a significant improvement in conceptual understanding with a large effect size for both part A (Q4A) and part B (Q4B). Since the fluid is flowing through a horizontal and constant diameter pipe, it is easier for the student to apply the fluid continuity and predict the correct velocity. Although all the results are not favorable, incorporation of the hydraulic loss DLM in the undergraduate classroom is very beneficial, as there is a significant improvement of ~25% in the overall mean score with a 99% confidence level and medium effect size.

3.2.2 Venturi meter

Student performance on the pre-test and posttest for the venturi meter experiment is shown in Fig. 5. For each question, assessment scores of post DLM activity are greater, which indicates an improvement in the student conceptual understanding. Q1 is a remember/understand level question in Bloom's taxonomy [12] as it just requires recalling the facts about fluid continuity. Students usually get to know this type of question very well through traditional lectures, which are reflected by the high average score in the pretest. Therefore, room for improvement in conceptual understanding is limited. But we still see ~6% improvement in the post DLM assessment with a small effect size. In Q2, students were asked to select the most realistic pressure profile along the axis of the venturi. This is a very high-level question in Bloom's taxonomy since it requires the student to make connections between ideas/concepts. As a result, the pre-DLM assessment shows a very low average score. Since the see-through nature of the DLMs makes the pressure profile visible, significant improvement with a >99.9% confidence level and a large effect size (> 0.8) is observed for this question. In Q3, students were asked to select the most realistic velocity profile along the axis of the venturi. The pre-DLM assessment shows a higher average score for velocity than the pressure profile (Q2) because students had previous knowledge about continuity from lectures and implementation of the hydraulic loss experiment. As velocity is not directly visible/observable, the improvement is not significant with the student t-test. However, practically there is >15% improvement in the average score from pre-DLM assessment to post DLM assessment which is reflected by the medium effect size. In addition, post-DLM assessment scores for pressure (Q2) and velocity (Q3) questions are similar which indicates that, from the DLM activity, the students also understand the energy transformation from one form to another occurring in a real fluid flowing through a pipe with variable diameter. This type of energy transformation phenomenon for an opposite system, sudden expansion in diameter, is tested in Q4. The statistics for this question further validate that there is a significant improvement in conceptual understanding with a 95% confidence level and medium effect size. Q5 also falls along this line, as it requires predicting the pressure profile from the given velocity profile. Therefore, like the previous question, the results of this question also show significant improvement in student conceptual understanding with a 95% confidence level and medium effect size. This further confirms the fact that our venturi DLM provides a solid understanding of the energy transformation concept in fluid flow. In Q6, students were asked to select the most realistic pressure profile along the axis of a piping system that goes through an expansion and then contraction opposite to that of the venturi. Like the venturi (Q2), the pre-assessment score is very low. However, after the DLM activity, the understanding level is changed significantly with a 99% confidence level and medium effect size. Since the student needs to translate knowledge from one scenario (venturi) to another scenario (opposite to venturi), this question falls into the analyze category in Bloom's taxonomy. These results show that our implementation of the venturi DLM is very effective for higher Bloom's level questions. Overall, implementation of venturi DLM yielded a >25% improvement in average scores with > 99.9% confidence level and high effect size.

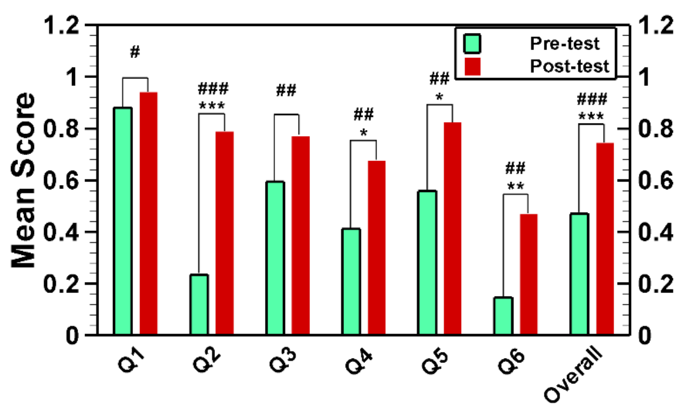


Fig. 5. Assessment results for venturi meter module implementation (N=17). #, ##, and ### indicates small, medium, and large Cohen's d effect size, respectively; while *, **, and *** indicates 0.05 ≤ p-value < 0.01, 0.01 ≤ p-value < 0.001 and p-value ≤ 0.001, respectively.

3.2.3 Double pipe heat exchanger

Fig. 6 shows the student performance on the pre-test and posttest in the case of the double pipe heat exchanger implementation. In Q1, students were asked to select the appropriate system boundary for an energy balance to find the heat transfer rate. This question falls under the analyze category of Bloom's taxonomy because answering this question requires understanding the system concept, using the information in a new situation, and drawing connections among ideas. Therefore, we should expect an improvement in understanding after the DLM implementation as we found DLM works better for higher Bloom's level questions. However, among 14 students, only one student correctly identified the system boundary in both the pre- and posttest. This result highlights the struggle that students have with applying the system boundary concept to a piece of equipment. The distinction between fluid flow area and heat transfer area is a principal concept in heat exchanger design and analysis. Implementation of our DLM in the undergraduate classroom helps the student to understand this concept as the assessment for Q2 shows a significant improvement in understanding after the DLM activity with a 95% confidence level and medium effect size. In Q3, students were asked to compare the heat transfer rate of two heat exchangers where one heat exchanger is double in length of the other heat exchanger. As shown by the assessment results, students had a good understanding of this concept before the DLM activity (Q3A). However, there was a lack in the reasoning part and the DLM activity helps in this part as the improvement is significant with a high effect size (Q3B). In Q4, students were asked to predict the heat transfer rate if the annular side fluid velocity is increased by altering the outer tube shape. Since our DLM has a fixed shape, the DLM activity does not offer any opportunity to address this concept. As a result, there is no improvement (or even drop) in understanding after the DLM activity. A similar result is observed for Q5 where students were asked to identify the driving potential for the heat transfer. We found that temperature measurements only at the inlet and outlet of the heat exchanger mislead students as most of them select the difference between inlet and outlet temperature of cold or hot fluids as the driving potential for heat transfer. Therefore, a little increase in the score might occur by chance. Q6 was designed to assess the student's comprehension of how cold-water flow rate and temperature affect the hot water outlet temperature. Like Q4 and Q5, no improvement in score is seen even though this was an activity in the experiment. Although the results for the double pipe DLM implementation are not as effective as those for the hydraulic loss or venturi experiment, overall, there is still ~7% improvement in the post DLM assessment from the pre-DLM assessment.

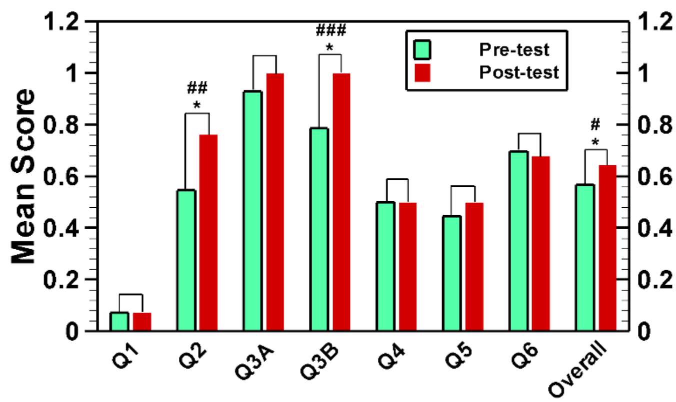


Fig. 6. Assessment results for double pipe heat exchanger module implementation (N=14). #, ##, and ### indicates small, medium, and large Cohen's d effect size, respectively; while *, **, and *** indicates 0.05 ≤ p-value < 0.01, 0.01 ≤ p-value < 0.001 and p-value ≤ 0.001, respectively

3.2.4 Shell and Tube Heat Exchanger

The student performance on the pre-test and posttest in the case of the shell-and-tube heat exchanger implementation is shown in Fig. 7. Although many concepts remain same between double-pipe and shell-and-tube heat exchangers, different regions of the shell-and tube heat exchangers have different types of flow. Q1 was used to measure student's understanding level for these flow types. As shown by the pre- and posttest scores, student's understanding level for this question has increased significantly with a medium effect size after the DLM implementation. The see-through nature of the DLM and inevitable bubbles entrained in the flow help students to visualize the flow pattern occurring inside the shell-and-tube heat exchanger, which in turn increases the understanding of different flow types. In Q2, students were asked to find the mathematical expression for crossflow area to calculate the shell-side fluid velocity. Again, the see-through nature of the DLM helps to realize the flow path for the shell-side fluid which eventually leads to better comprehension of the flow area. Because of that, post-DLM assessment shows an improvement with a medium effect size. In Q3, students were asked to evaluate the effect of a larger number of baffles on the heat transfer rate. However, both pre- and posttest scores are the same which indicates no improvement in understanding level after the use of the DLM. The effect of a higher number of baffles on heat transfer rate is not straightforward as it requires making the connection between several ideas. In addition, the current shell-and-tube heat exchanger DLM has a fixed number of baffles, therefore, there is no provision to study the heat transfer rate with a higher number of baffles. In Q4, students were asked about the effect of the inlet temperatures of the cold and hot fluids on the heat transfer rate. This concept was addressed by experimenting with three different inlet conditions; therefore, we should expect an improvement in performance after the DLM activity. The assessment result is in line with our expectation as it shows an improvement from pre- to posttest by ~15% with a small effect size. In Q5, we asked students to quantify the shell-side fluid velocity from the volumetric flow rate. Although this was addressed by the DLM implementation, the result is not favorable as it shows a decrease in understanding level. Further study is needed to identify the root cause of this result. Like a double pipe heat exchanger, in Q6, we asked students to analyze the influence of cold-water flow rate on hot water outlet temperature. We demonstrated this concept during the DLM implementation by manipulating the cold-water flow rate. As a result, students were able to grasp the concept as shown by the results (Q6A). Students also perform better in the reasoning part (Q6B). Although Q5 yields a drop in score, overall, DLM implementation was beneficial for the students as there is >15% improvement with a medium effect size.

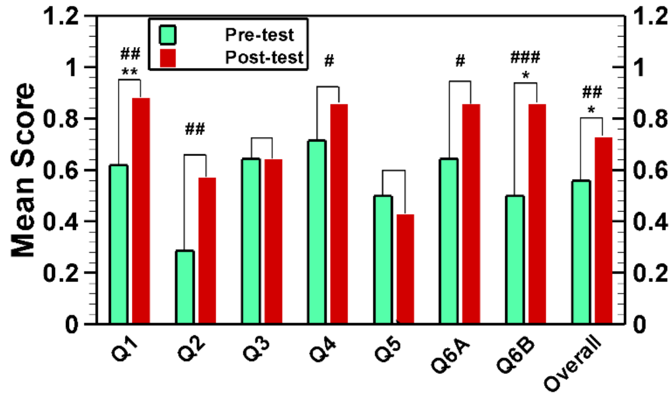


Fig. 7. Assessment results from shell & tube heat exchanger module implementation (N=14). #, ##, and ### indicates small, medium, and large Cohen's d effect size, respectively; while *, **, and *** indicates 0.05 ≤ p-value < 0.01, 0.01 ≤ p-value < 0.001 and p-value ≤ 0.001, respectively.

4. Conclusions

We have developed four desktop modules to incorporate hands-on learning in the undergraduate classroom to teach transport courses in the Chemical and Mechanical engineering disciplines. In this paper, we have addressed the design, fabrication, and classroom implementation for those four injection-molded desktop learning modules. These modules are fabricated with polycarbonate plastic, which ensures transparency, excellent reproducibility of results, and low cost. Dimensional consistency and structural integrity are also ensured by the robot-assisted assembly with UV-curable adhesive. Comparison of experimental data with corresponding theoretical prediction reveals the usefulness of DLMs for the accurate measurement of major loss, flow rates, and heat transfer rates. Implementation in the undergraduate classroom reveals that DLMs are useful for teaching different transport phenomena-related concepts. There is a definitive increase in overall student understanding level with the demonstration of DLMs. The small-scale and low cost makes the DLM highly flexible for a variety of classroom applications. Therefore, it can be concluded that the DLMs can be used to provide effective hands-on or virtual learning experiences to undergraduate Chemical and Mechanical engineering students.

Acknowledgments

This work was supported by the National Science Foundation (NSF) under grant 1821578. The authors also acknowledge the support from the WSU machine shop, and undergraduates Connor Backman, Jose Becerra Fernandez, Andrea Garcia, Julio Gaspar, Carter Grant, Chase Llewellyn, Anthony Mendoza, Sara Moore, Johnathan Powell, Aline Uwase, Carah Watson, and Chandler Young who assisted with DLM assembly, and the students at the University of Central Oklahoma who participated in the implementation.

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